PRELIMINARY EVALUATION OF A VACUUM-INDUCED CONCENTRATED-LOAD SANDWICH TESTER

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PRELIMINARY EVALUATION OF A VACUUM-INDUCED CONCENTRATED-LOAD SANDWICH TESTER[1]

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Summary

This progress report presents a description of a testing device designed to aid in the inspection of aircraft sandwich constructions. Included is a discussion of the performance of the tester on a limited number of sandwich constructions. Results of a theoretical analysis for determining deflections and maximum stresses are presented. Suggestions are given for improving the performance of the device.

Introduction

Increasing use of sandwich construction, particularly for primary structural elements, has created a greater demand for inspection devices to determine the quality of sandwich constructions. Various methods have been suggested and some successfully demonstrated to locate and explore the extent of unbonded areas. Obviously, a testing device would be most useful if a nondestructive test could be made that would not only locate but would also

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[1] This progress report is one of a series prepared and distributed by the Forest Products Laboratory under U. S. Navy, Bureau of Aeronautics Order No. NAer 01319 and U. S. Air Force No. USAF-18(600)-70. Results here reported are preliminary and may be revised as additional data become available.

[2] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

evaluate the strength of poorly bonded areas. A vacuum tester was devised and patented by an aircraft company.[3] This vacuum tester was submitted to the Forest Products Laboratory for test at the request of the Air-Force-Navy-Civil Panel 23.

Description and Operation of the Sandwich Tester

The tester consists of a dish-shaped casting, approximately 10 inches in diameter, with a rubber gasket or washer around the outside rim. Figure 1 shows an external view of the device. The gasket is used to form a pressure seal between the tester and a sandwich panel. An internal view of the tester (fig. 2) shows a central rubber-covered steel foot that is pressed against the panel as the dish-shaped cavity is evacuated. Foot sizes of different diameters from 1 to 2 inches in steps of 1/4 inch are supplied so that various ratios of compression and shear can be applied. The foot is fastened by means of a convenient snap-on fitting to a threaded bolt that extends through the casting. A vacuum gage is attached to the casting to measure the applied load.

In use, the tester is operated by placing it on a sandwich panel, adjusting the position of the foot by turning the threaded bolt until the panel contacts both the foot and the rubber gasket, and drawing a vacuum on the casting until failure occurs or until some desired proof load, determined by the setting on the poppet valve, is reached.

Exploratory trials of the tester showed that the rubber gasket may be deformed so much, by the deflection of the panel, that the casting makes contact with the sandwich. If this occurs, continued evacuation merely places small additional uniform load on the sandwich with little further deflection. This can be easily demonstrated by applying the tester to a thin sheet of aluminum; the casting makes contact with the sheet at low vacuum and then the sheet is slightly concave around the foot until maximum vacuum is attained.

In order to indicate rim contact, a buzzer was introduced in a circuit between the casting and sandwich facing. If a nonconductive facing material is on the sandwich being tested, thin strips of metal foil can be placed on the surface and used in the circuit.

If rim contact occurs at low loads, the vacuum can be partially released and the foot extended toward the sandwich by turning the foot adjusting screw.

It was conceivable that some sandwich constructions would deform considerably under test with no visible or audible indication of failure.

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[3]Devised by R. M. Matlock and patented by Lockheed Aircraft Corporation. Licenses for manufacture and use granted to Aircraft Die Cutters, Los Angeles, Calif., and Zenith Plastics, Gardena, Calif.

Indications of failure might appear on a load-deflection curve. Accordingly, a deflection dial was arranged to read the central deflection of the sandwich with reference to three points located opposite the rim of the tester. The arrangement of this apparatus is shown in figure 3. It was subsequently demonstrated that failure of a balsa core was apparent on load-deflection curves (fig. 4), but after failure the load increased until rim contact occurred and eventually increased to maximum vacuum with no audible signs of failure.

Stresses Induced by the Tester

Of primary interest are compression and shear stresses induced in the core of the sandwich construction by the concentrated load at the foot of the tester. Failures that may occur in the bond between facings and core can be interpreted in terms of the shearing stress developed in the core.

The area covered by the casting and gasket of the tester decreases slightly as the vacuum is increased as a result of deformation of the gasket. The area of the tester used at the Forest Products Laboratory was computed to be 90.76 square inches. From this area the compressive and shear stresses in the core were calculated according to the values in table 1.

The expressions given in table 1 were obtained from approximations of the formulas given in the appendix of this report. For unusual constructions having either thick facings or extremely soft cores the more exact expressions in the appendix should be used to compute the stresses. Expressions for deflections and facing stresses are also included in the appendix.

Experimental Work

In order to determine whether the tester would perform satisfactorily in measuring the quality of sandwich constructions, a few panels were tested to determine either core shear strengths, the location of unbonded areas, or the strength of poorly bonded areas.

For more accurate load readings the dial vacuum gage was replaced with a mercury column, shown in figure 3. A needle valve was placed in the vacuum line to permit sensitive adjustment of load application.

A preliminary test on a sandwich having 0.012-inch 24ST clad aluminum facings on a core of end-grain balsa wood 1/4 inch thick developed core failures in shear at approximately the shear strength of the balsa as evaluated in shear tests. Load-deflection curves for this construction are shown in figure 4.

Preliminary testing on a sandwich panel known to have unbonded areas demonstrated that the tester was capable of detecting the unbonded areas

regardless as to whether the unbonded facing was the one on which the tester was applied or whether it was the opposite one.

As a further check on the performance of the tester, two flat panels were tested of each of two sandwich constructions. One panel of each construction was well bonded and one panel was poorly bonded on one side. Poor bonding was obtained by using less adhesive than is required for good bonding. The constructions were (1) 0.020-inch 24ST clad aluminum facings bonded with adhesive 35 to a 1/2-inch-thick core of aluminum honeycomb of 0.003-inch foil formed to 3/8-inch cell size (core 52), and (2) facings of 8 plies of glass cloth 112-114 impregnated with resin 2, wet-laminated to a 1/2-inch-thick core of glass-cloth honeycomb of 112-114 cloth formed to 1/4-inch cell size (core 36).

Each panel was large enough to permit four tests with the tester (two from each side) without overlapping the test areas. Load-deflection curves for the aluminum panel are given for each test in figure 5 and for the glass-cloth panel in figure 6. Values of the shear stresses developed by the tester at failure are given in table 2. The average strength values as measured by the tester show that the poorly bonded aluminum panel had approximately 80 percent of the strength of the well-bonded panel and that the poorly bonded glass-cloth panel had approximately 35 percent of the strength of the well-bonded panel. Figure 7 shows a cross section through an aluminum control panel (the two halves laid face to face) that illustrates a typical failure under the foot of the tester, and figure 8 shows a typical bond failure in a control glass-cloth panel. Poorly bonded panels of both types failed in a similar manner, respectively, except that the aluminum panels failed in the poor bond as well as in shear in the core, and the bond failures in the poorly bonded glass-cloth panels were more extensive.

After the tests had been made with the tester, the panels were cut into minor coupons to be tested in bending to determine shear strength, and in tension normal to the facings to determine bond strength. The bending specimens were 1 inch wide and were tested under loads applied at two-third points on a total span of 6 inches for the aluminum sandwich and 4-1/2 inches for the glass-cloth sandwich. The strong direction of the core was placed parallel to the span length. Tensile specimens were 1 by 1 inch in cross section. The results of these tests are also given in table 2.

The shear strengths as determined for the bending-test coupons were from 30 percent to 70 percent of the shear strengths as determined by the tester. The bending-test coupons were cut from portions of the panel adjacent to the area tested by the tester, and, therefore, this reduction in shear strength may have been due to damage caused by the tester load or may also have been due to stresses caused by the saw when the minor coupons were cut.

Shear strengths as determined from bending tests showed the poorly bonded aluminum panel to have 88 percent of the strength of the well-bonded panel, and the poorly bonded glass-cloth panel to have 19 percent of the strength of the well-bonded panel.

Tensile strengths of the poorly bonded aluminum panel were 27 percent of the strengths of the well-bonded panel, and strengths of the poorly bonded glass-cloth panel were 11 percent of the strengths of the well-bonded panel.

General Observations

In the evaluation work on the tester to date, it appears that the device has considerable promise of providing a practical means of proof-loading flat, and possibly curved, sandwich panels to a precalculated stress. The addition of the spring loaded relief valve provides a means for controlling the load to any desired level within the range of 1 to 24 inches of mercury. The accuracy of the load application appears to be about $\pm 1/2$ inch of mercury. The trials showed that tests can be made at the rate of 12 to 15 per minute if load-deflection data are not obtained.

Conclusions

The tester can be used to determine the location of unbonded or poorly bonded areas in panels of sandwich construction.

Although the data of this report do not positively show direct correlation, the tester may be used to determine shear strengths of sandwich constructions.

In the realm of nondestructive testing the tester should find use in careful application of certain proof loads as an aid in inspection of the quality of sandwich panels.

APPENDIX

The deflection and the stresses induced in the facings and in the core by the tester have been analyzed by the use of formulas derived in U. S. Forest Products Laboratory Report No. 1828.[4] In that report the core and facing materials are assumed to be isotropic and, consequently, the present results are limited to this special case.

In order to carry out the analysis, the distribution of load over the foot of the tester must be specified. An attempt has been made to keep the distribution uniform by covering the foot with a rubber gasket, and it is possible that at small vacuum loads it actually is quite uniform. At large vacuum loads, however, the tester forces the panel to bend, and the load is possibly concentrated more heavily at the rim of the foot than at the center. On the basis of these considerations, the analysis has been carried out for two assumed distributions, namely, (1) a load uniformly distributed over the foot, and (2) a load concentrated at the rim of the foot. For a given vacuum a uniform distribution yields higher predicted shear stress in the core and lower bending stresses in the facings than a load concentrated at the rim of the foot. It is expected that if the true distribution of load over the foot of the tester could be determined, the results would be intermediate between those of the two extreme cases considered.

The formulas given below are derived on the assumptions that the test panel is of infinite extent and that the facings are of equal thickness. Moreover, the formulas are given in forms applicable to a panel with thin facings and with a core that, like end-grain balsa, has a relatively high shear modulus. Specifically, it is assumed that αa and αb, defined below, are so large that the Bessel functions that appear in formulas taken from Report No. 1828[4] can be expressed in the forms (64) and (65) of that report, and that the quantity $\underline{e^{-\alpha(a-b)}}$ can be neglected in comparison with unity. It is believed that these conditions will be fulfilled for most constructions that are likely to be of practical interest.

The deflection and the components of stress in the facings and in the core are given in terms of the following symbols:

$\underline{a}$: radius of the tester gasket

$\underline{b}$: radius of the foot

$\underline{c}$: thickness of the core

$$\underline{E} = \frac{E_f}{1 - \gamma^2}$$

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[4] W. S. Ericksen. The Bending of a Circular Sandwich Panel under Normal Load.

E_f: Young's modulus of the facing material

f: thickness of the facings

G: shear modulus of the core material

$I = I_m + I_f$

$$I_m = \frac{f(c + f)^2}{2}$$

$$I_f = \frac{f^3}{6}$$

q: applied vacuum (p.s.i.)

$$\alpha^2 = \frac{2GI}{EcfI_f}$$

ν: Poissons ratio of facing material

For a load distributed uniformly over the foot of the tester, the deflection of the sandwich, w_U, at the center of the tester relative to the outer rim of the tester is given by the formula

$$w_U = w_{bU} + w_{sU} \qquad (1)$$

where,

$$w_{bU} = \frac{qa^2}{64EI}\left[5(a^2 - b^2) - 4b^2 \log \frac{a}{b}\right] \qquad (2)$$

$$w_{sU} = \frac{qa^2}{2EI_f\alpha^2}\left[\log \frac{a}{b} - \frac{2}{\alpha^2 b^2}\right] \qquad (3)$$

For a load concentrated at the rim of the foot, the central deflection is given by

$$w_c = w_{bc} + w_{sc} \qquad (4)$$

where,

$$w_{bc} = \frac{qa^2}{64EI}\left[5a^2 - 8b^2 \left(1 + \log \frac{a}{b}\right)\right] \qquad (5)$$

$$w_{sc} = \frac{qa^2}{2EI_f\alpha^2}\left[\log \frac{a}{b} - \frac{1}{2}\left(1 + \frac{1}{\alpha b}\right)\right] \qquad (6)$$

The shear stress in the core evaluated at the rim of the foot is given by the formula

$$\tau_U = \frac{q}{2(c + f)} \left[\frac{a^2 - b^2}{b} - \frac{a^2}{\alpha b^2} \right] \tag{7}$$

for a load distributed uniformly over the foot, and by the formula

$$\tau_c = \frac{q}{2(c + f)} \left[\frac{a^2}{2b} - b \right] \tag{8}$$

for a load concentrated at the rim of the foot.

The stress at the outer surface of the facing upon which the tester is placed is evaluated at the rim of the foot by the formula

$$\sigma_{U,c} = - \frac{q(c + 2f)}{32I} \left[m_{bU,c} + \frac{16(c + f)\ (3c + 2f)}{f(c + 2f)} m_{sU,c} \right] \tag{9}$$

where the subscripts U and c again designate quantities associated with a uniform foot load and a load concentrated at the rim of the foot, respectively.

For a load distributed uniformly over the foot,

$$m_{bU} = 4(1 + \gamma)\ a^2 \log \frac{a}{b} - (3 + \gamma)\ (a^2 - b^2) \tag{10}$$

$$m_{sU} = \frac{(1 + \gamma)\ (a^2 - b^2)}{2\alpha^2 b^2} - \frac{a^2}{2\alpha^2 b^2} \left[1 - \frac{(1 - \gamma)}{\alpha b} \right] \tag{11}$$

and for a load concentrated at the rim of the foot,

$$m_{bc} = 4(1 + \gamma)\ a^2 \log \frac{a}{b} - 2(1 + \gamma)\ a^2 + (3 + \gamma)\ b^2 \tag{12}$$

$$m_{sc} = \frac{a^2}{4\alpha b} \left[1 - \frac{(1 - \gamma)}{\alpha b} \right] - \frac{1 + \gamma}{\alpha^2} \tag{13}$$

At the present time a reliable means of estimating the transverse pressure on the core is not available. However, if the load can be taken to be uniformly distributed over the foot, it is estimated that the pressure exerted by the loaded facing upon the core is about one-half the pressure on the foot.

Application of formulas

Figure 4 shows the load-central deflection curve for a test panel to which the preceding formulas are applicable. The results given below were

obtained from these formulas for a foot diameter of 1-3/4 inches. In the computations, the shear modulus of the core material, which was not measured, was taken as 20,000 pounds per square inch. The following is a complete list of the dimensions and elastic properties used.

$\underline{a}$ = 5.38 inches

$\underline{b}$ = 0.875 inch

$\underline{c}$ = 0.25 inch

$\underline{E_f}$ = 10^7 pounds per square inch

$\underline{f}$ = 0.012 inch

$\underline{G}$ = 2×10^4 pounds per square inch

$\gamma = 0.3$

These yield

$\underline{E}$ = 1.1×10^7 pounds per square inch

$\underline{I_m}$ = 4.12×10^{-4} inches^3

$\underline{I_f}$ = 2.88×10^{-7} inches^3

$\underline{I}$ = 4.12×10^{-4} inches^3

$\alpha = 41.6$

From (2) and (3) it is found that the deflections are given by

$$w_{bU} = 0.0135\ q$$

and (14)

$$w_{sU} = 0.0049\ q$$

Therefore, if the load is uniformly distributed over the foot, the central deflection obtained from (1) is

$$w_U = 0.0184\ q_{(p.s.i.)} = 0.0090\ q_{(in.\ HG)} \qquad (15)$$

Similarly, from (5) and (6)

$$w_{bc} = 0.0127\ q$$

and (16)

$$w_{sc} = 0.0034\ q$$

so that for a load concentrated at the rim of the foot, (4) yields

$$w_c = 0.0161\, q_{(p.s.i.)} = 0.0079\, q_{(in.\ HG)} \tag{17}$$

Formulas (15) and (17) yield, respectively,

$$q_{(in.\ HG)} = 111\, w_U \quad \text{and} \quad q_{(in.\ HG)} = 127\, w_c \tag{18}$$

The slopes of the lines represented by these equations would change slightly if the shear modulus of the core was changed and if the radius of the tester, which presumably decreases with increasing load, was varied. They are, however, of the same order of magnitude as the slopes of the linear portions of the two curves in figure 4 for the foot diameter of 1-3/4 inches, which are 125 and 132. It is of interest to observe that the deflections due to shear represented by w_{sU} and w_{sc} are about one-third of the deflections due to bending represented by w_{bU} and w_{bc}. These relatively large shear deformations for an aluminum-balsa panel are attributed to the small dimensions of the area of the panel over which deflection takes place.

The shear stress in the core obtained from (7) and (8) are, respectively,

$$\tau_U = 60\, q_{(p.s.i.)} = 29\, q_{(in.\ HG)} \tag{19}$$

and

$$\tau_c = 30\, q_{(p.s.i.)} = 15\, q_{(in.\ HG)} \tag{20}$$

The stress predicted on the basis of a uniform load on the foot is thus about twice as great as that obtained by taking the load to be concentrated at the rim of the foot.

For the present core and facing thicknesses, formula (9) for determining facing stresses takes the form

$$\sigma_{U,c} = -20.8\, qm_{bU,c} - 20,300\, qm_{sU,c} \tag{21}$$

From formulas (10) to (13)

$$20.8\, m_{bU}q = 3760\, q \tag{22}$$

$$20,300\, m_{sU}q = 267\, q \tag{23}$$

$$20.8\, m_{bc}q = 4170\, q \tag{24}$$

$$20,300\, m_{sc}q = 3950\, q \tag{25}$$

Therefore, for the load distributed uniformly over the foot, the stress at the surface of the facing at the rim of the foot is

$$\sigma_U = -3927\ q_{(p.s.i.)} = -1930\ q_{(in.\ HG)} \qquad (26)$$

and for the load concentrated at the rim of the foot the corresponding stress is

$$\sigma_c = -8120\ q = -3990\ q_{(in.\ HG)} \qquad (27)$$

The minus sign in these equations indicates a compressive stress. Formula (27) indicates that if the load on the foot was concentrated at the rim, the proportional-limit stress of 27,000 pounds per square inch would be reached at 6.6 inches of mercury.

Table 1.--Stresses induced by the tester

Diameter of foot	Core stresses	
	Compression[1] [2] σ	Shear[1] τ
In.	P.s.i.	P.s.i.
1.00	57.2q	$57.2 \frac{q}{h + c}$
1.25	36.5q	$45.6 \frac{q}{h + c}$
1.50	25.2q	$37.8 \frac{q}{h + c}$
1.75	18.4q	$32.2 \frac{q}{h + c}$
2.00	13.9q	$27.8 \frac{q}{h + c}$

[1] q = applied vacuum (p.s.i.), h = total sandwich thickness (in.), c = core thickness (in.)

[2] See Appendix, page 12.

Table 2.--Strengths of panels as determined by the tester

Shear strengths				Tensile strength	
Well-bonded panel		Poorly bonded panel		Well-bonded panel	Poorly bonded panel
Tester	Bending test	Tester	Bending test		
(1)	(2)	(3)	(4)	(5)	(6)
P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.
Sandwich Construction: Facings -- 0.020-inch 24ST Clad Aluminum, Core -- 1/2-inch-thick Aluminum Honeycomb of 0.003-inch Foil Formed to 3/8-inch Cell Size[1]					
191	78	[2]163	76	370	110
242	95	[2]170	156	330	110
211	179	163	142	350	100
204	196	170	56	320	70
....	86	....	163	310	70
....	175	....	....	230	60
....	....	....	....	230	70
....	....	....	....	250	60
....	....	....	....	270	50
....	....	....	....	280	60
....	....	....	....	280	50
....	....	....	....	270	80
....	....	....	....	300	110
....	....	....	....	270	100
....	....	....	....	250	100
....	....	....	....	340	....
....	....	....	....	340	....
....	....	....	....	300	....
....	....	....	....	310	....
....	....	....	....	310	....
Av. 212	135	166	119	296	80

(Sheet 1 of 2)

Table 2.--Strengths of panels as determined by the tester (Cont.)

Shear strengths				Tensile strength	
Well-bonded panel		Poorly bonded panel		Well-bonded panel	Poorly bonded panel
Tester	Bending test	Tester	Bending test		
(1)	(2)	(3)	(4)	(5)	(6)
P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.
Sandwich Construction: Facings -- 8 plies of Glass Cloth 112, Core -- 1/2-inch-thick Glass-cloth Honeycomb of 112 Cloth Formed to 1/4-inch Cell Size[3]					
451	180	[2]146	38	310	0
544	252	[2]213	66	270	40
521	340	151	50	250	60
515	354	185	52	240	20
	226			420	30
	282			220	0
				340	20
				290	50
				300	50
				230	50
				290	
				240	
				340	
				280	
				290	
				300	
				280	
				320	
				290	
				300	
Av. 506	272	174	52	290	32

[1]Tested with a 2-inch-diameter foot.

[2]Tester on poor-bond side of sandwich.

[3]Tested with a 1-1/2-inch-diameter foot.

(Sheet 2 of 2)

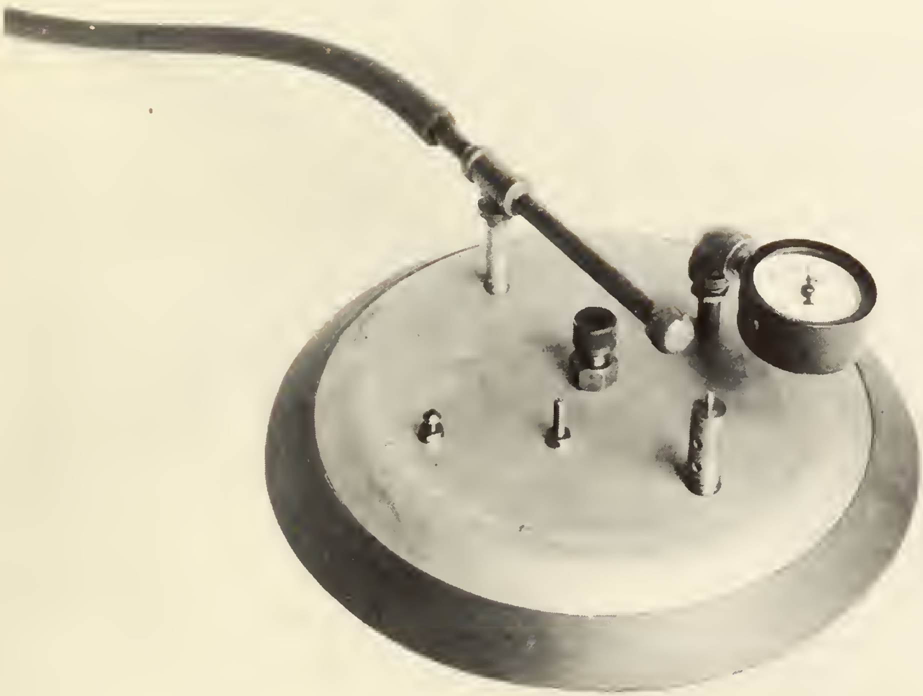


Figure 1.--External view of the sandwich tester, showing rubber gasket, attached vacuum line, and vacuum gage. The center bolt extends to the interior foot. An auxiliary poppet valve has been installed (immediately below the gage on the photograph) for control of vacuum during use as a tester.

Z M 88041 F

Figure 2.--Internal view of the tester, showing the central foot and alternate foot sizes available for use. The cantilever spring actuating the poppet valve for control of vacuum is also shown.

Z M 88040 F

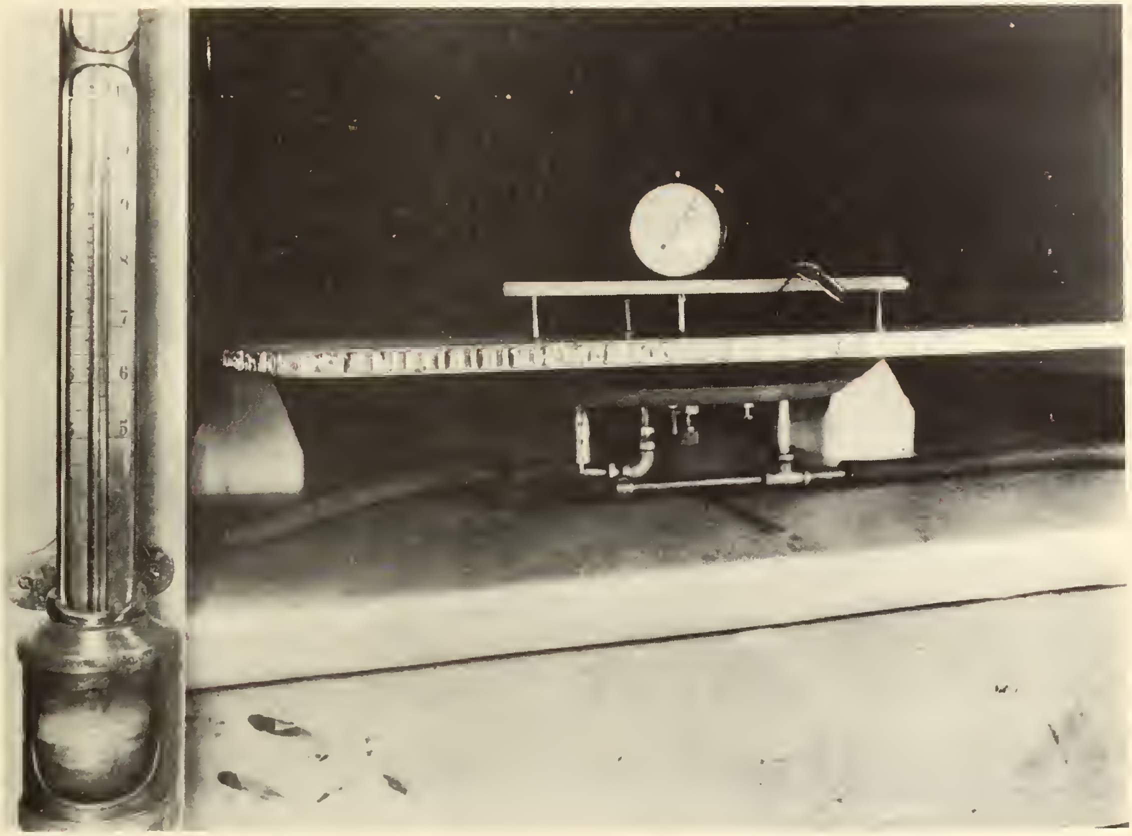
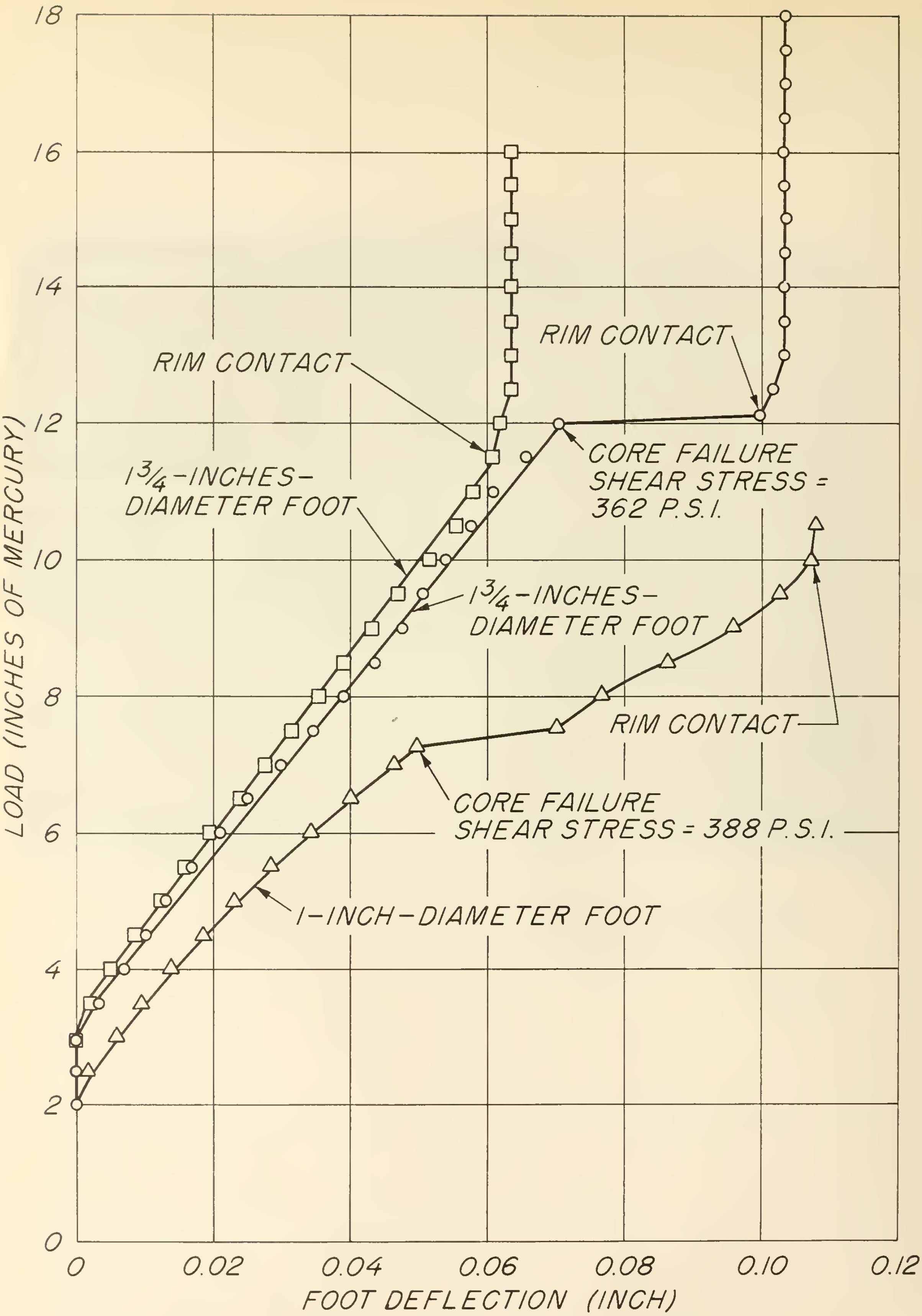


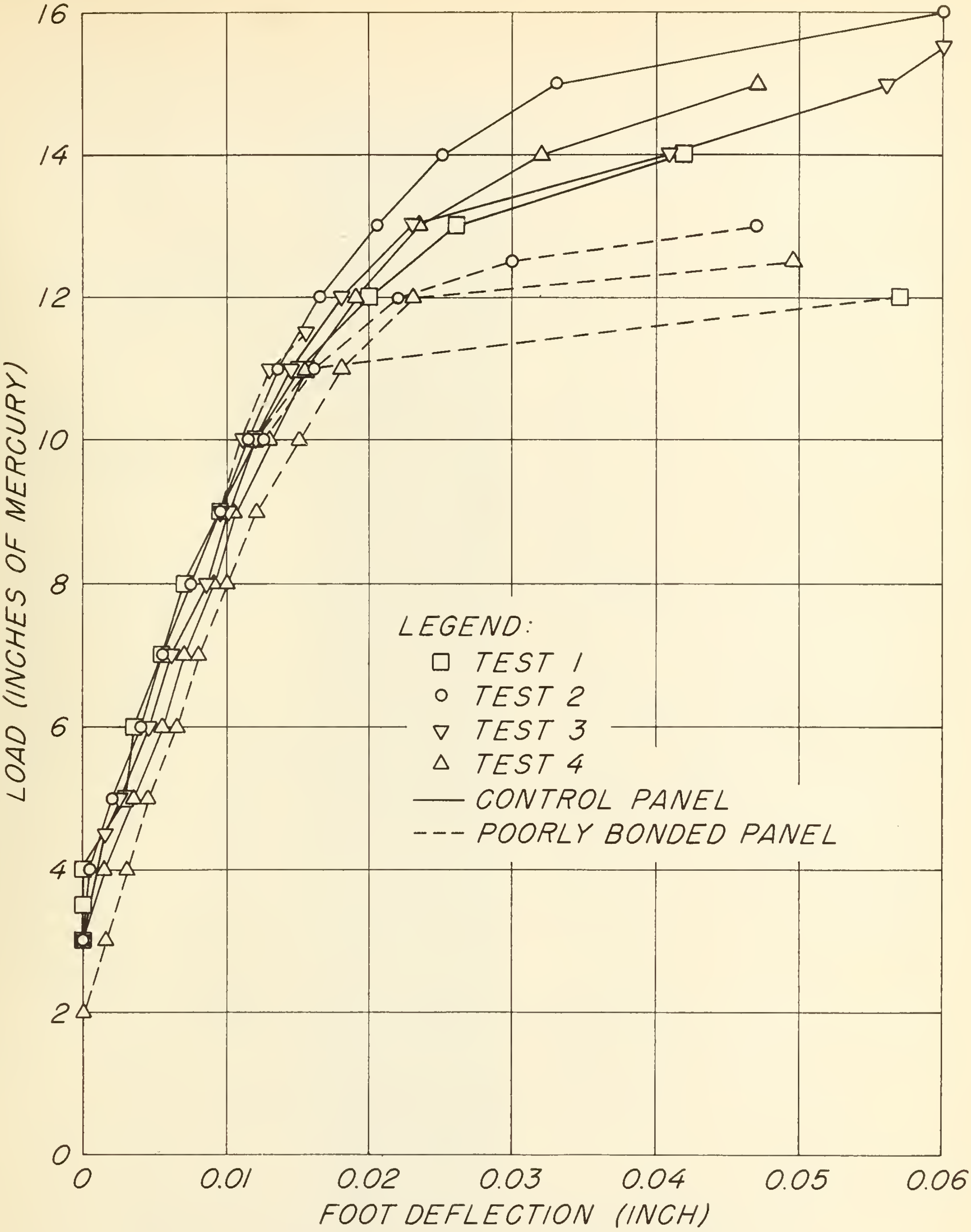
Figure 3.--The tester in use during evaluation tests, showing the addition of a deflection-measuring device on the opposite facing.

z M 88038 F



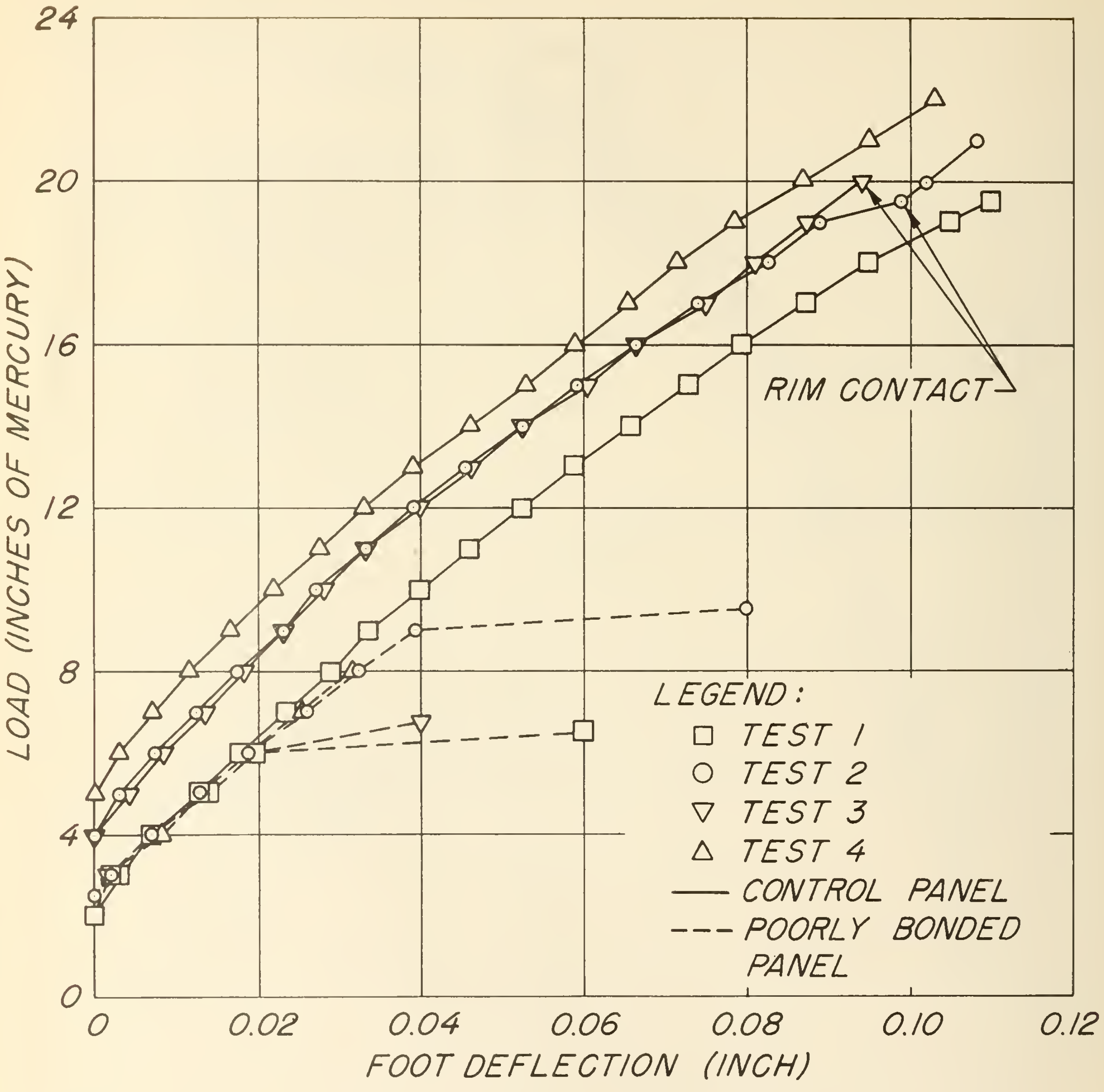
Z M 90070 F

Figure 4.--Load-deflection curves produced by applying tester to a sandwich having 0.012-inch 24ST clad aluminum facings on a 1/4-inch-thick core of end-grain balsa.



Z M 90071 F

Figure 5.--Load-deflection curves produced by applying tester with a 2-inch-diameter foot to a sandwich having 0.020-inch 24ST clad aluminum facings on a 1/2-inch-thick core of 0.003-inch aluminum foil formed to 3/8-inch hexagonal cells.



Z M 90072 F

Figure 6.--Load-deflection curves produced by applying tester with a 1-1/2-inch-diameter foot to a sandwich having facings of eight plies of glass cloth 112-114 on a 1/2-inch-thick core of glass cloth 112-114 formed to a honeycomb of 1/4-inch cell size.

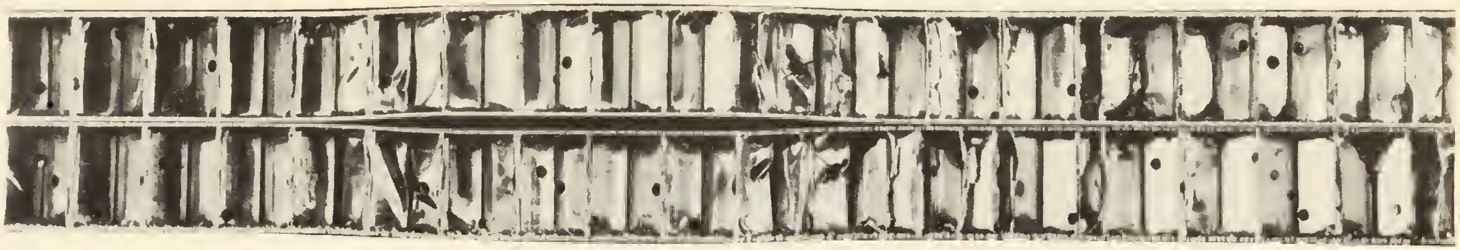


Figure 7.--Cross section through failed portion of an aluminum honeycomb control panel (the two halves laid face to face), showing distortion and shear failures in core. There was no evidence of bond failure in any of the aluminum control panels.

Z M 88862 F

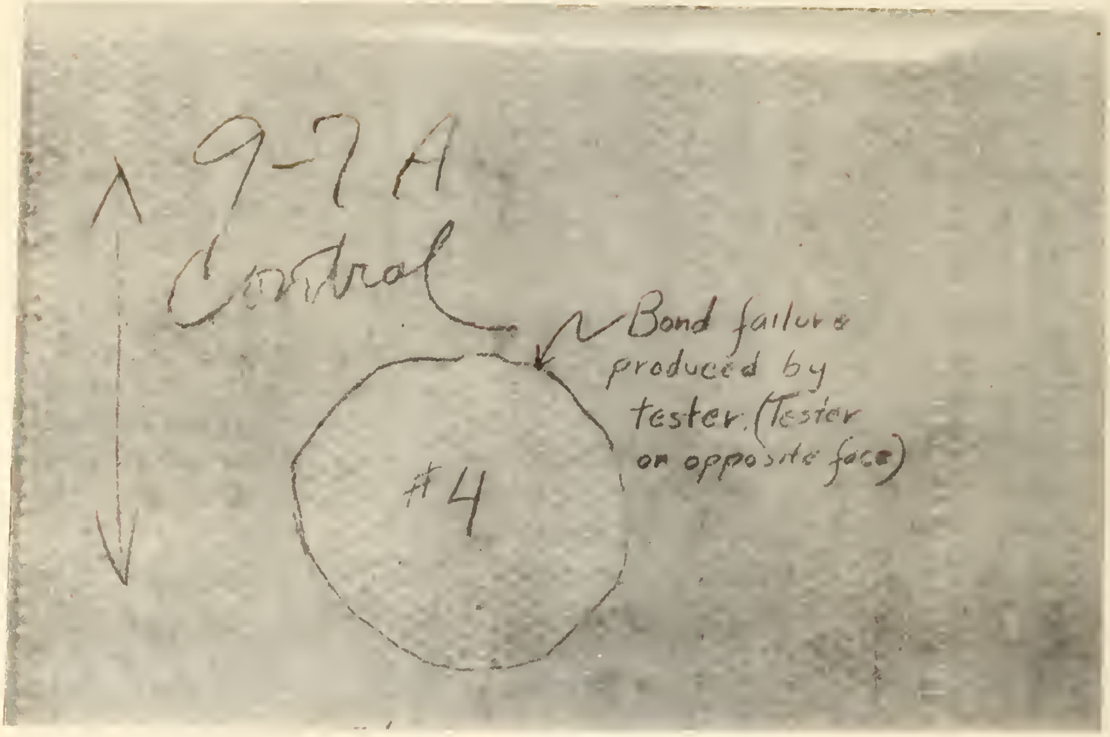


Figure 8.--Typical failure in a control glass-cloth panel. Failure is confined to the bond between the facing and the core on the side opposite the tester.

Z M 88863 F